Indian Journal of Ecology (2025) 52(5) (SI): 1260-1267
DOI: https://doi.org/10.55362/IJE/2025/4643

Manuscript Number: 4643
NAAS Rating: 5.38

Assessing Biomass Production and Carbon storage in Agroforestry Systems Located at Proximity Gradients to Gobind Sagar Reservoir

S. Sarvade, D.R. Bhardwaj[1], B. Gupta[1], Prem Prakash[1], Dhirender Kumar[1] Prashant Sharma[1], C.L. Thakur[1], Manish Kumar[2] and Varun Attri[3]

Department of Forestry, Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur-482 004, India
[1]Department of Silviculture and Agroforestry, Dr. Y. S. Parmar University of Horticulture and Forestry, Solan-173 230, India
[2]ICAR- Central Soil Salinity Research Institute, Karnal-132 001, India
[3]Regional Research Station, Punjab Agricultural University, Ballowal Saunkhri, Balachur-144 521, India
**E-mail: somanath553@gmail.com*

Abstract: This study assessed biomass and carbon storage dynamics across different agroforestry systems and distance gradients from a reservoir. Biomass estimation was carried out using stratified quadrat sampling for trees and crops, with carbon stock quantified as the sum of the aboveground and belowground components. There was significant variation in the total carbon storage among agroforestry systems and across distance classes, with their interaction effect also being noteworthy ($P = 0.429$). The home garden system exhibited the highest carbon stock (54.05 t ha^{-1}), while the agri-silviculture system recorded the lowest (29.42 t ha^{-1}). Across spatial gradients, carbon stocks declined with increasing distance from the reservoir, ranging from 45.69 t ha^{-1} at D1 (0-2 km), to 29.95 t ha^{-1} at D7 (12-14 km). The combined influence of management practices, species composition, and site conditions plays a decisive role in carbon accumulation. These findings affirm that diversified and intensively managed agroforestry systems, particularly home gardens, have greater potential for enhancing carbon storage than less diversified systems.

Keywords: Agroforestry systems, Aboveground biomass & carbon, Below ground biomass and carbon, Distance gradient

Agroforestry, the deliberate integration of trees with crops and/or livestock, is widely acknowledged as a land use practice that delivers multiple ecological, economic, and social benefits. Among its various ecosystem services, the ability to generate substantial biomass and sequester atmospheric carbon dioxide makes agroforestry a crucial strategy for climate change mitigation (Jose 2009, Thakur et al., 2011, Singh et al., 2015, Chaturvedi et al., 2016, Luna et al., 2016). Trees in these systems act as long-term carbon sinks, storing carbon in their biomass (Bhusara et al., 2016, Singh et al., 2019, Rakshita et al., 2025) and soils while also contributing to soil fertility, nutrient cycling, and biodiversity enhancement (Sarvade et al., 2014a, Sarvade et al., 2016a, Sarvade et al., 2019, Thakur et al., 2024). Furthermore, agroforestry moderates microclimatic extremes, reduces soil erosion, and provides timber, fodder, fruits, and fuelwood, ensuring livelihood security for rural communities (Sarvade et al., 2014b, Thakur et al., 2015). In the context of increasing climate variability, its role in balancing productivity with environmental conservation is gaining global recognition (Sharma et al., 2022).

The spatial arrangement of agroforestry systems plays a significant role in determining the biomass production and carbon storage potential. Factors such as soil moisture availability, nutrient status, and microclimatic conditions can vary considerably depending on the proximity to water bodies (Sarvade et al., 2016a, 2016b). The Gobind Sagar Reservoir in Himachal Pradesh, formed by the construction of the Bhakra Dam on the Sutlej River, exerts a notable influence on the surrounding agroforestry landscapes (Anonymous 2005, Sarvade 2024). These systems are distributed across multiple distance classes from the reservoir, where hydrological influences, soil characteristics, and human management practices interact to shape vegetation growth and productivity (Wu et al., 2004). Understanding how these spatial gradients impact biomass and carbon dynamics can provide valuable insights for targeted land use planning and climate resilience.

The varied topography and climatic diversity of Himachal Pradesh create favorable conditions for a wide range of agroforestry models. The presence of the Gobind Sagar Reservoir adds an additional layer of hydrological moderation, potentially improving soil moisture regimes and supporting higher biomass yields near the water body (Degu et al., 2011, Sarvade et al., 2016a. Sarvade et al., 2016b). Studies from other regions have indicated that proximity to reservoirs is often correlated with increased tree growth rates and biomass accumulation due to stable water availability and moderate temperature fluctuations. However, little research has been conducted to examine how these proximity effects translate into variations in carbon sequestration potential, particularly in the Himalayan foothill agroforestry context. This knowledge gap limits our ability to optimize agroforestry systems for both ecological and economic gains.

Evaluating biomass production and carbon sequestration across different proximity classes in the Gobind Sagar Reservoir offers dual benefits: advancing scientific understanding and guiding sustainable land management (Sarvade et al., 2016a, Sarvade et al., 2016b). Insights from such research can help policymakers and local communities design agroforestry interventions that maximize carbon capture, while enhancing productivity and income generation. Furthermore, quantifying these patterns contributes to accurate regional carbon accounting, which is a key requirement for implementing climate-smart agricultural and forestry programs. These findings also support participation in carbon credit mechanisms, providing additional financial incentives for farmers to adopt and maintain tree-based systems.

Against this backdrop, the present study aimed to investigate biomass yield and carbon storage dynamics in different agroforestry systems located at varying distances from the Gobind Sagar Reservoir. By systematically comparing agroforestry systems across defined proximity gradients, this study sought to identify patterns of spatial variation, determine the key environmental and management factors influencing biomass and carbon levels, and recommend strategies to enhance their carbon sequestration potential. Such an approach will not only deepen our understanding of reservoir-influenced landscapes, but also support the broader agenda of climate change mitigation and sustainable rural development in Himachal Pradesh.

MATERIAL AND METHODS

Study area: This research was conducted in the vicinity of the Gobind Sagar Reservoir, situated within the upper sub-basin of the Satluj Basin (Code: 13) in Bilaspur district, Himachal Pradesh. Geographically, the district lies between latitudes 31°12′30″ and 31°35′45″ N and longitudes 76°23′45″ and 76°55′40″ E, encompassing a total area of 1,167 km², equivalent to approximately 2.1% of the state's geographical expanse (Sarvade et al., 2016a , 2016b). The terrain spans elevations from 290 to 1,980 m above mean sea level, with a substantial portion of the district lying below 650 m a. s.l.. The study area falls under the sub-mountain, low-hill tropical subtropical zone of the Himachal Pradesh. Based on 10-year averages (2005-2014), temperatures ranged from 3.53°C (January) to 23.20°C (July) for minimum and 19.38°C (January) to 36.19°C (May) for maximum. Monsoon rainfall varied between 104.49 mm (June) and 309.97 mm (August), with annual averages of 1,106.12 mm and marked inter-seasonal and inter-annual fluctuations, notably higher in 2006, 2007, and 2013 (Sarvade 2024).

A total of 25 sites were selected to address the study objectives, strategically distributed across seven concentric distance zones, each 2 km wide, surrounding the Gobind Sagar Reservoir designated as D1 (0-2 km), D2 (2-4 km), D3 (4-6 km), D4 (6-8 km), D5 (8-10 km), D6 (10-12 km), and D7 (12-14 km). These sites are located within SLJU020, SLJU021, SLJU022, and SLJU023 catchment. The distribution included six sites in D1 and D2, three sites in D3, D4, and D6, two sites in D5, and 2 in D7. Detailed site information is shown in Figure 1.

Sample collection and data analysis: In the agroforestry systems, biomass and carbon estimations were carried out through stratified quadrat sampling. For tree components, three quadrats of 15m × 15m were demarcated, while 1m × 1m quadrats were employed for crop components, following the guidelines of Muller-Dombois and Ellenberg (1974). The agroforestry systems in the study area were classified according to the structural attributes and spatial arrangement of the constituent plant species. Tree measurements were recorded once during the study period, whereas crop sampling was performed at the harvest stage of the growing season to capture the maximum biomass accumulation.

Biomass estimation: The biomass of all vegetation strata (trees and crops) was assessed to estimate aboveground biomass (AGB), belowground biomass (BGB), and total biomass (TB) in all identified agroforestry systems. A destructive sampling method was employed for crops. All individuals occurring within the designated quadrats were harvested, separated by species, and partitioned into shoot and root components. Plant parts were oven-dried at 70 ± 5°C to a constant weight, and biomass was expressed in tonnes ha^{-1}. Belowground herbaceous biomass was obtained by excavating a soil monolith of 25 cm × 25 cm × 30 cm, whereas shrub roots were extracted manually, washed thoroughly, and oven-dried for biomass determination (Gupta et al., 2009). Diameter at breast height (DBH) and total height were recorded using tree calipers and Spiegel Relaskop, respectively. Tree volume was estimated using species- and region-specific volume equations (FSI 2006, 2012). The aboveground tree biomass was calculated by multiplying the stem volume by species-specific wood density and biomass expansion factors (Dixon et al., 1993; 1994; IPCC, 2007), whereas belowground biomass was derived as 25% of the aboveground biomass following IPCC (1996).

Carbon storage estimation: Carbon storage in the different vegetation layers was calculated using biomass-derived values. For herbaceous, crop, and shrub species, both aboveground and belowground carbon densities were estimated by multiplying the respective biomasses with a carbon conversion factor of 0.45 (Woomer 1999). For trees, aboveground carbon stock was obtained by applying factors suggested by the IPCC (2007), whereas belowground tree carbon was estimated using a conversion factor of 0.45 (Woomer 1999).

Statistical analysis: To evaluate the variations among land use systems and distance classes from the reservoir across the 25 study sites, two-way analysis of variance was performed. Post-hoc comparisons were carried out using the least significant difference at significance threshold of $P < 0.05$. All statistical analyses were conducted using SPSS software package version 23 (IBM Corp 2015).

RESULTS AND DISCUSSION

Aboveground biomass (AGB): Among the systems, the highest aboveground biomass was under HG (90.14 t ha^{-1}), which was significantly superior to all other systems (Table 1). In contrast, the lowest value was observed under AS (48.56 t ha^{-1}), which remained statistically comparable (P =

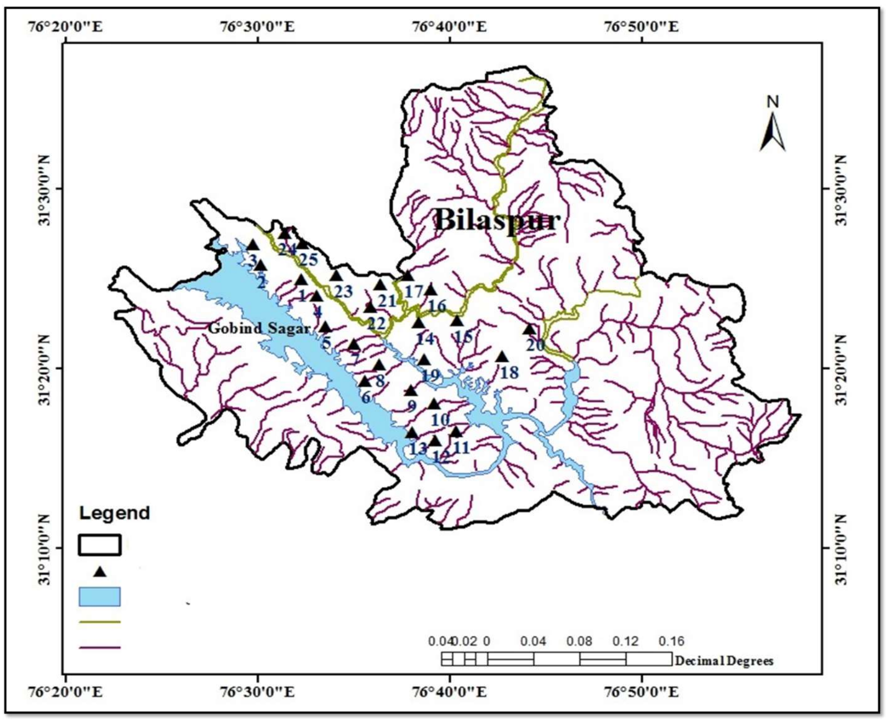

Fig. 1. Study sites selected in upstream catchment area of Gobind Sagar reservoir

Table 1. Aboveground biomass production (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	61.90 ±7.97	72.55 ± 8.57	64.10 ± 8.63	67.04 ± 15.30	111.76 ± 15.80	75.47
D2	54.55 ± 13.39	64.66 ± 12.88	53.50 ± 11.51	72.69 ± 2.09	95.80 ± 11.24	68.24
D3	48.36 ± 4.81	47.60 ± 7.97	43.17 ± 1.14	59.29 ± 7.06	94.55 ± 10.00	58.59
D4	43.70 ± 5.98	54.68 ± 7.04	55.04 ± 6.28	58.48 ± 10.39	90.17 ± 2.14	60.41
D5	48.90 ± 7.55	59.58 ± 0.93	55.64 ± 8.60	62.63 ± 0.89	92.53 ± 1.32	63.86
D6	42.08 ± 2.55	48.90 ± 8.79	52.96 ± 2.15	48.33 ± 3.61	75.17 ± 11.81	53.49
D7	40.44 ± 4.16	47.76 ± 3.39	47.10 ± 5.18	41.70 ± 3.48	71.04 ± 5.18	49.61
Mean	48.56	56.53	53.07	58.59	90.14	61.38
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

DFR = Distance from Reservoir; AFs = Agroforestry systems; AS = Agri-silviculture; AH = Agri-horticulture; ASH = Agri-silvi-horticultre; AHS = Agri-horti-silviculture; HG = Home gardens

0.212) with ASH (53.07 t ha^{-1}). Across distance classes, aboveground biomass peaked significantly at D1 (75.47 t ha^{-1}) and showed a gradual decline with increasing distance from the reservoir, following the order: D2 (68.24 t ha^{-1}) > D5 (63.86 t ha^{-1}) > D4 (60.41 t ha^{-1}) > D3 (58.59 t ha^{-1}) > D6 (53.49 t ha^{-1}) > D7 (49.61 t ha^{-1}). The significant interaction was also observed between agroforestry systems and distance classes, with the maximum biomass observed under HG at D1 (111.76 t ha^{-1}) and the minimum under AS at D7 (40.44 t ha^{-1}).

These findings highlight the synergistic role of tree-crop integration in enhancing aboveground biomass productivity. Improved soil fertility under agroforestry conditions coupled with complementary spatial arrangements of tree and crop components facilitates better utilization of available light, water, and nutrients. Furthermore, site-specific factors, such as slope and soil texture, modulate biomass accumulation, thereby reinforcing the ecological advantages of agroforestry systems (Das et al., 2008, Gera et al., 2011, Holzmueller and Jose 2012, Kanime et al., 2013).

Belowground biomass (BGB): The HG system exhibited the maximum BGB (19.83 t ha^{-1}), which was significantly higher than that of the other systems (Table 2). Conversely, the AS system showed the minimum BGB (11.28 t ha^{-1}), which remained statistically comparable with ASH (12.16 t ha^{-1}). Across distance gradients, D1 recorded the highest BGB (17.48 t ha^{-1}), while the lowest was obtained at D7 (11.32 t ha^{-1}), statistically similar to D3 (13.18 t ha^{-1}) and D6 (12.10 t ha^{-1}). The significant interaction effect between system types and distance classes was evident, with the maximum BGB under HG at D1 (25.36 t ha^{-1}) and the minimum under AS at D7 (9.35 t ha^{-1}). The highlight that root biomass dynamics in agroforestry systems are not only system-dependent but also strongly influenced by proximity to water sources. Higher root proliferation under HG may be attributed to efficient resource capture and favorable soil microenvironments, whereas lower values in AS reflect limited rooting capacity and reduced belowground allocation. Variations along distance gradients suggest that soil moisture availability, fertility status, and microclimatic conditions governed by the reservoir play a decisive role. Additionally, tree-crop interactions, inherent soil characteristics, and management interventions, such as spacing and pruning, significantly contribute to the observed differences in BGB (Das et al., 2008, Kanime et al., 2013, Sarvade et al., 2016b, Sarvade 2024).

Total biomass (TB): The analysis revealed that both main effects were highly significant, with a notable interaction effect (Table 3). Among the systems, HG accumulated the maximum total biomass (109.97 t ha^{-1}), followed by AHS, AH and ASH, whereas the minimum was in AS (59.84 t ha^{-1}). Across distance gradients, TB was highest at D1 (92.95 t ha^{-1}) and lowest at D7 (60.92 t ha^{-1}). The interaction of system and distance further demonstrated that HG at D1 stored the greatest amount of biomass (137.12 t ha^{-1}), while AS at D7 registered the least (49.79 t ha^{-1}). The observed variation in biomass across systems and distances underscores the role of management interventions that improve soil fertility, reduce interspecific competition, and enhance overall system productivity (Swarup et al., 2000; Hati et al., 2006). Biomass accumulation in agroforestry is further shaped by the type and proportion of tree-crop components, planting geometry, and availability of critical growth resources, such as soil moisture and light (Das et al., 2008, Das and Das 2010, Gera et al., 2011, Holzmueller and Jose 2012, Kanime et al., 2013). ASH systems contributed substantially (72.92%) to fruit and fodder tree components, a trend consistent with the findings of Singh (2014) in the Giri watershed of Himachal Pradesh. More broadly, system productivity is the outcome of interacting ecological factors,

Table 2. Belowground biomass production (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	14.56 ± 2.05	17.28 ± 2.82	14.77 ± 2.01	15.44 ± 3.69	25.36 ± 4.92	17.48
D2	12.74 ± 3.17	14.91 ± 3.40	12.34 ± 2.65	16.85 ± 0.84	20.96 ± 2.92	15.56
D3	11.14 ± 1.24	10.95 ± 1.53	9.85 ± 0.40	13.39 ± 1.46	20.55 ± 2.19	13.18
D4	10.23 ± 1.30	12.40 ± 1.42	12.50 ± 1.34	12.99 ± 2.17	19.62 ± 0.43	13.55
D5	11.20 ± 1.62	13.43 ± 0.14	12.73 ± 1.94	13.99 ± 0.35	19.96 ± 0.35	14.26
D6	9.75 ± 0.53	11.04 ± 1.87	12.09 ± 0.50	11.05 ± 0.93	16.55 ±2.13	12.10
D7	9.35 ± 1.12	11.04 ± 0.80	10.83 ±1.27	9.60 ± 0.60	15.78 ± 0.48	11.32
Mean	11.28	13.01	12.16	13.33	19.83	13.92
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

including climate, soil properties, floristic diversity, and species phenology, as emphasized by Bahar (2003).

Above ground carbon (AGC): There was significant effect of both factors with HG recording the maximum AGC (55.88 t ha^{-1}), significantly higher than all other systems (Table 4). The lowest value was under AS (24.28 t ha^{-1}), which statistically comparable with ASH (26.54 t ha^{-1}). Across distance gradients, AGC was highest at D1 (37.73 t ha^{-1}) and declined progressively with increasing distance, reaching its minimum at D7 (24.80 t ha^{-1}). The significant interaction effect was also observed, with the maximum AGC recorded under HG at D1 (55.88 t ha^{-1}) and the minimum under AS at D7 (20.22 t ha^{-1}). Greater AGC accumulation under HG highlights the synergistic role of tree-crop interactions supported by favorable soil and climatic conditions (Das et al., 2008, Gera et al., 2011, Jose and Bardhan 2012). Declining AGC at greater distances from the reservoir may be linked to enhanced soil erosion and associated fertility loss, which adversely affects the carbon storage capacity (Mahmoudi et al., 2010). Singh (2014) also reported similar system-specific variations, with the agri-silvi-horticulture system showing the highest aboveground carbon (31.56 t C ha^{-1}), followed by agri-horti-silviculture, agri-silviculture and agri-horticulture . These findings collectively emphasize that system composition, resource availability, and site conditions act in concert to regulate aboveground carbon dynamics in agroforestry landscapes.

Below ground carbon (BGC): The agroforestry systems and distance classes from the reservoir exerted a significant influence with the maximum BGC recorded under HG (8.97 t ha^{-1}) (Table 5). The minimum was in AS (5.14 t ha^{-1}), which remained statistically comparable with ASH (5.53 t ha^{-1}). Across distance gradients, the highest BGC was observed at D1 (7.95 t ha^{-1}), while the lowest was recorded at D7 (5.14 t ha^{-1}), which did not differ significantly from D3, D4, D5 and D6. The interaction effect was also significant with HG at D1 accumulating the maximum BGC (11.52 t ha^{-1}) and AS at D7 recording the least (4.26 t ha^{-1}). The decline in the BGC with increasing distance from the reservoir indicates the influence of soil degradation, declining fertility, harsher microclimatic conditions, and higher anthropogenic pressures (Mahmoudi et al., 2010, Gera et al., 2011, Kanime et al., 2013). The

Table 3. Total biomass production (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	76.46 ± 9.99	89.82 ± 11.36	78.87 ± 10.64	82.47 ± 18.92	137.12 ± 20.52	92.95
D2	67.30 ± 16.55	79.56 ± 16.22	65.84 ± 14.17	89.54 ± 2.74	116.75 ± 14.14	83.80
D3	59.50 ± 6.04	58.55 ± 9.49	53.02 ± 1.52	72.68 ± 8.52	115.10 ± 12.17	71.77
D4	53.93 ± 7.28	67.08 ± 8.46	67.54 ± 7.63	71.48 ± 12.55	109.79 ± 2.48	73.96
D5	60.10 ± 9.17	73.01 ± 1.07	68.37 ± 10.54	76.62 ± 1.24	112.49 ± 1.67	78.12
D6	51.83 ± 3.05	59.94 ± 10.65	65.05 ± 2.65	59.39 ± 4.54	91.72 ± 13.93	65.59
D7	49.79 ± 5.28	58.80 ± 4.19	57.93 ± 6.44	51.30 ± 4.08	86.82 ± 5.66	60.92
Mean	59.84	69.54	65.23	71.92	109.97	75.30
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

Table 4. Aboveground carbon storage (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	30.95 ± 3.98	36.27 ± 4.28	32.05 ± 4.31	33.52 ± 7.65	55.88 ± 7.90	37.73
D2	27.28 ± 6.69	32.33 ± 6.44	26.75 ± 5.76	36.34 ± 1.05	47.90 ± 5.62	34.12
D3	24.18 ± 2.41	23.80 ± 3.98	21.58 ± 0.57	29.65 ± 3.53	47.27 ± 5.00	29.30
D4	21.85 ± 2.99	27.34 ± 3.52	27.52 ± 3.14	29.24 ± 5.20	45.08 ± 1.07	30.21
D5	24.45 ± 3.78	29.79 ± 0.47	27.82 ± 4.30	31.32 ± 0.45	46.27 ± 0.66	31.93
D6	21.04 ± 1.27	24.45 ± 4.39	26.48 ± 1.08	24.17 ± 1.81	37.59 ± 5.91	26.74
D7	20.22 ± 2.08	23.88 ± 1.70	23.55 ± 2.59	20.85 ± 1.74	35.52 ± 2.59	24.80
Mean	24.28	28.27	26.54	29.30	45.07	30.69
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

superior BGC under HG suggests that system composition and management practices can enhance belowground carbon allocation through improved rooting depth and soil resource capture. Singh (2014) also observed that agri-silvi-horticulture systems stored the maximum belowground carbon (9.43 t C ha^{-1}), followed by agri-horti-silviculture agri-silviculture and agri-horticulture (6.86 t C ha^{-1}). These results underline the pivotal role of system design, soil conditions, and distance-induced ecological gradients in regulating belowground carbon storage in agroforestry landscapes.

Total carbon (TC): The total carbon stock (AGC + BGC) from the crop and tree components was markedly influenced by both the agroforestry systems and the distance gradients from the reservoir, and interaction also had a significant impact on TC (Table 6). Among the systems, the home garden (HG) accumulated the maximum TC (54.05 t ha^{-1}), followed by AHS , AH, ASH and the lowest in AS (29.42 t ha^{-1}). Across the spatial classes, the highest TC stock was observed at the nearest distance D1 (45.69 t ha^{-1}), declining progressively with distance, reaching the minimum at D7 (29.95 t ha^{-1}). The interaction pattern highlighted that the HG system at D1 stored the maximum carbon (67.40 t ha^{-1}), whereas the lowest was in AS at D7 (24.48 t ha^{-1}). These variations can be attributed to system-specific management interventions that enhance soil fertility, reduce tree-crop competition, and subsequently promote higher biomass accumulation and carbon retention (Swarup et al., 2000, Hati et al., 2006, Murthy et al., 2013). Singh (2014) also reported that agri-silvi-horticulture systems achieved the highest TC stock (40.99 t C ha^{-1}), followed closely by agri-horti-silviculture (39.49 t C ha^{-1}), while agri-silviculture (31.57 t C ha^{-1}) and agri-horticulture (30.29 t C ha^{-1}) stored relatively lower carbon. The grand total carbon stock in agroforestry systems is modulated by factors such as tree-crop combinations, planting geometry, site edaphic characteristics, and prevailing climatic conditions (Maikhuri et al., 2000, Das and Chaturvedi 2005, Das and Chaturvedi 2008, Gera et al., 2011, Nair 2012, Kanime et al., 2013). Supporting this, Roshetko et al. (2002) demonstrated that tree-based land use sequesters substantially more carbon than croplands or grasslands under comparable ecological settings. Similarly, Saha and Jha (2012) reported a wide variation (12 to 228 Mg ha^{-1}) with a median of 95 Mg ha^{-1}

Table 5. Belowground carbon storage (t ha^{-1}) in agroforestry systems (AFs) at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	30.95 ± 3.98	36.27 ± 4.28	32.05 ± 4.31	33.52 ± 7.65	55.88 ± 7.90	37.73
D2	27.28 ± 6.69	32.33 ± 6.44	26.75 ± 5.76	36.34 ± 1.05	47.90 ± 5.62	34.12
D3	24.18 ± 2.41	23.80 ± 3.98	21.58 ± 0.57	29.65 ± 3.53	47.27 ± 5.00	29.30
D4	21.85 ± 2.99	27.34 ± 3.52	27.52 ± 3.14	29.24 ± 5.20	45.08 ± 1.07	30.21
D5	24.45 ± 3.78	29.79 ± 0.47	27.82 ± 4.30	31.32 ± 0.45	46.27 ± 0.66	31.93
D6	21.04 ± 1.27	24.45 ± 4.39	26.48 ± 1.08	24.17 ± 1.81	37.59 ± 5.91	26.74
D7	20.22 ± 2.08	23.88 ± 1.70	23.55 ± 2.59	20.85 ± 1.74	35.52 ± 2.59	24.80
Mean	24.28	28.27	26.54	29.30	45.07	30.69
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

Table 6. Total carbon storage (t ha^{-1}) in agroforestry systems at different distance classes from reservoir

DFR	Agroforestry systems (Mean ± SD)					Mean
	AS	AH	ASH	AHS	HG	
D1	37.59 ± 4.92	44.15 ± 5.59	38.77 ± 5.23	40.54 ± 9.30	67.40 ± 10.10	45.69
D2	33.08 ± 8.14	39.11 ± 7.97	32.36 ± 6.96	44.01 ± 1.35	57.38 ± 6.95	41.19
D3	29.25 ± 2.97	28.78 ± 4.66	26.06 ± 0.75	35.72 ± 4.19	56.56 ± 5.99	35.27
D4	26.51 ± 3.58	32.97 ± 4.16	33.20 ± 3.75	35.13 ± 6.16	53.95 ± 1.21	36.35
D5	29.54 ± 4.51	35.89 ± 0.53	33.61 ± 5.18	37.66 ± 0.61	55.28 ± 0.82	38.39
D6	25.48 ± 1.50	29.46 ± 5.24	31.97 ± 1.31	29.19 ± 2.23	45.07 ± 6.84	32.24
D7	24.48 ± 2.60	28.90 ± 2.06	28.47 ± 3.17	25.21 ± 2.01	42.67 ± 2.77	29.95
Mean	29.42	34.18	32.06	35.35	54.05	37.01
P value	0.001 (AFs);		0.001 (DFR);		0.01 (AFs × DFR)	

in the carbon sequestration potential of different agroforestry systems across the North-Eastern Hill Regions, reinforcing the high potential of diversified systems for long-term carbon storage.

CONCLUSION

The study reaffirm that agroforestry systems hold immense potential as nature-based solutions for climate change mitigation, while simultaneously supporting rural livelihoods. Home gardens, with their multi-strata structure and high species diversity, have emerged as the most effective model for maximizing carbon sequestration, while agri-silviculture systems have demonstrated relatively lower storage potential. Importantly, the proximity effect observed near the reservoir highlights the role of microclimatic conditions, soil moisture regimes, and landscape position in influencing carbon accumulation, suggesting that site-specific factors must be integrated into agroforestry planning. For broader applicability, this study emphasizes that diverse, well-managed agroforestry models should be prioritized across various ecological and socioeconomic settings worldwide. Incorporating multipurpose trees, shrubs, and crops in a scientifically designed planting geometry not only enhances carbon storage, but also delivers co-benefits such as soil conservation, biodiversity enrichment, and food and nutritional security. Therefore, governments, policymakers, and development agencies should promote home gardens, agri-horti-silviculture, and similar diversified systems as part of climate-smart land management strategies. In a global context, these results suggest that reservoir catchments, river basins, and other ecologically fragile zones can be rehabilitated effectively through agroforestry interventions. Scaling up such practices contributes to achieving international climate commitments (Paris Agreement, SDGs 13 and 15) and also address the livelihood needs of local communities. Thus, agroforestry represents a win-win pathway to reconcile climate mitigation with sustainable rural development worldwide.

AUTHOR's CONTRIBUTION

SS, DRB, and BG initiated and conceptualized the study, wrote, and reviewed the manuscript. PP, DK, and PS contributed to data evaluation, writing, and reviewing the manuscript. MK and VA contributed to the field data collection and laboratory work.

REFERENCES

Anonymous 2005. *Unravelling Bhakra: Assessing the temple of resurgent India*. Manthan Adhyayan Kendra, Badwani, India. 201p.

Bahar N 2003. Vegetation dynamics and biomass production of undergrowth vegetation in *Eucalyptus tereticornis* plantation. *Indian Forester* **129**(11): 1361-1369.

Bhusara JB, Thakur NS and Hegde HT 2016. Biological yield and carbon sequestration in prominent traditional agroforestry systems in Valsad District, Gujarat, India. *Indian Journal of Ecology* **43**(1): 318-320.

Chaturvedi OP, Handa AK, Kaushal R, Uthappa AR, Sarvade S and Panwar P 2016. Biomass production and carbon sequestration through agroforestry. *Range Management and Agroforestry* **37**: 116-127.

Das DK and Chaturvedi OP 2005. Structure and function of *Populus deltoides* agroforestry systems in eastern India: 1. Dry matter dynamics. *Agroforestry Systems* **65**: 215-221.

Das DK and Chaturvedi OP 2008. Root biomass and distribution of five agroforestry tree species. *Agroforestry Systems* **74**: 223-230.

Das DK, Chaturvedi OP, Mandal MP and Kumar R 2008. Effect of tree plantations on biomass and primary productivity of herbaceous vegetation in eastern India. *Tropical Ecology* **49**(2): 95-101.

Das T and Das AK 2010. Litter production and decomposition in the forested areas of traditional homegardens: case study from Barak Valley, Assam, northeast India. *Agroforestry Systems* **79**: 157-170.

Degu AM, Hossain F, Niyogi D, Pielke Sr. R, Shepherd JM, Voisin N and Chronis T 2011. The influence of large dams on surrounding climate and precipitation patterns. *Geophysical Research Letters* **38**: 1-7.

Dixon RK, Wimjum JK, Lee JJ and Schroeder PE 1994. Integrated systems: assessing of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. *Climate Change* **30**: 1-23.

Dixon RK, Winjum JK and Schroeder PE 1993. Conservation and sequestration of carbon: potential of forest and agroforest management practices. *Global Environmental Change* **2**: 159-173.

FSI 2006. *Volume equations for forests of India, Nepal and Bhutan*. Forest Survey of India, Ministry of Environment and Forests, Govt. of India, Dehradun. 249 p.

FSI 2012. *Carbon stock in India's forests*. Forest Survey of India, Ministry of Environment and Forests, Govt. of India, Dehradun. 144 p.

Gera M, Mohan G, Bisht NS and Gera N 2011. Carbon sequestration potential of agroforestry under CDM in Punjab state of India. *Indian Journal of Forestry* **34**: 1-10.

Gupta B, Mehta R and Mishra VK 2009. Fire ecology of ground vegetation in *Pinus roxburghii* Sargent plantations in North-West Himalaya: floristic composition and species diversity. *Caspian Journal of Environmental Sciences* **7**(2): 71-78.

Hati KK, Mandal KG, Misra AK, Ghosh PK and Bandyopadhyay KK 2006. Effect or inorganic fertilizer and farmyard manure on soil properties, root distribution, and water-use efficiency of soybean in Vertisols of central India. *Bioresource Technology* **97**: 2182-2188.

Holzmueller EJ and Jose S 2012. Biomass production for biofuels using agroforestry: potential for the North Central Region of the United States. *Agroforestry Systems* **85**: 305-314.

IBM Corp 2015. *IBM SPSS Statistics for Window, Version 23.0*. Armonk, NY: IBM Corp.

IPCC 1996. *Land use, land use change and forestry*. *In*: Revised 1996 IPCC guidelines for national greenhouse gas inventories. Cambridge University Press, Cambridge, U.K.

IPCC 2007. *Climate change-synthesis report: contribution of working groups I, II and III to the fourth assessment report*.

Jose S 2009. Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems* **76**: 10

Jose S and Bardhan S 2012. Agroforestry for biomass production and carbon sequestration: overview. *Agroforestry Systems* **86**: 105-111.

Kanime N, Kaushal R, Tewari SK, Raverkar KP, Chaturvedi S and Chaturvedi OP 2013. Biomass production and carbon sequestration in different tree-based systems of Central Himalayan Tarai region. *Forests, Trees and Livelihoods* **22**: 38-50.

Luna RK, Thakur NS, Gunaga RP and Kumar V 2016. Biomass, carbon stock and carbon dioxide removal across different girth classes of eucalyptus species in Punjab: Implication for eucalyptus plantations. *Journal Tree Sciences* **35**(1): 13-20.

Mahmoudi B, Bakhtiari F, Hamidifar M and Danehkar A 2010. Effects of land use change and erosion on physical and chemical properties of water (Karkhe Watershed). *International Journal of Environmental Research* **4**(2): 217-228.

Maikhuri RK, Semwal RL, Rao KS, Singh K and Saxena KG 2000. Growth and ecological impacts of traditional agroforestry tree species in Central Himalaya, India. *Agroforestry Systems* **48**: 257-272.

Muller-Dumbois and Ellenberg DH 1974. *Aims and methods of vegetation ecology*. John Wiley and Sons. New York. 547 p.

Murthy IK, Gupta M, Tomar S, Munsi M, Tiwari R, Hegde GT and Ravindranath NH 2013. Carbon sequestration potential of agroforestry systems in India. *Earth Science & Climatic Change* **4**(1): 1-7.

Nair PKR 2012. Carbon sequestration studies in agroforestry systems: reality-check. *Agroforestry Systems* **86**: 243-253.

Rakshitha BK, Betageri S, Patgar VG and Kotresha K 2025. Estimation of tree biomass and carbon density of tropical moist deciduous forest in Semi-Arid Regions Katridaddi - Hillock, Belagavi, Karnataka. *Indian Journal of Ecology* **52**(2): 300-305.

Roshetko JM, Delaney M, Hairiah K and Purnomosidhi P 2002. Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage? *American Journal of Alternative Agriculture* **17**: 138-148.

Saha R and Jha P 2012. Carbon sequestration potentials of agroforestry systems under climate change scenario - brief review with special emphasis on North-Eastern Hill Regions. *Journal of Agricultural Physics* **12**(2): 100-106.

Sarvade S 2024. *Plant bio-resource dynamics around Gobind Sagar reservoir in Himachal Pradesh.* Ph.D. Thesis. Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan (Nauni) HP-173 230 India. 223p.

Sarvade S, Gautam DS, Upadhyay VB, Sahu RK, Shrivastava AK, Kaushal R, Singh R and Yewale AG 2019. *Agroforestry and soil health: An overview*. In: Inder D, Asha R, Kumar N, Singh R, Kumar D, Uthappa AR, Handa AK, Chaturvedi OP (Eds), *Agroforestry for climate resilience and rural livelihood*. Scientific Publishers, Jodhpur, Rajasthan, India, 275-297.

Sarvade S, Gupta B and Singh M 2016a. Composition, diversity and distribution of tree species in response to changing soil properties with increasing distance from water source-A case study of Gobind Sagar reservoir in India. *Journal of Mountain Science* **13**: 522-533.

Sarvade S, Gupta B and Singh M 2016b. Soil carbon storage potential of different land use systems in upstream catchment area of Gobind Sagar reservoir, Himachal Pradesh. *Indian Journal of Soil Conservation* **44** (2): 112-119.

Sarvade S, Singh R, Gumare V, Kachawaya DS and Khachi B 2014c. Agroforestry: An approach for food security. *Indian Journal of Ecology* **41**(1): 95-98.

Sarvade S, Singh R, Prasad H and Prasad D 2014a. Agroforestry practices for improving soil nutrient status. *Popular Kheti* **2**(1): 60-64.

Sharma P, Bhardwaj DR and Singh MK 2022. Geospatial technology in agroforestry: Status, prospects, and constraints. *Environmental Science and Pollution Research* **30**: 116487-116487.

Singh M 2014. *Pattern, composition and vegetation dynamics of agroforestry systems in Giri Catchment, HP* (Ph.D. Thesis). Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.), India. 215 p.

Singh M, Gupta B, Sarvade S and Awasthe RK 2015. Biomass and carbon sequestration potential in different agroforestry systems in giri catchment of North Western Indian Himalayas. *Indian Journal of Agroforestry* **17**(2): 42-48.

Singh R, Bhardwaj DR, Pala NA and Rajput BS 2019. Biomass production and carbon stock potential of natural vegetation, agroforestry and cultivated land use systems along altitudinal gradient in north western Himalayas. *Range Management and Agroforestry* **40**(1): 94-103.

Swarup A, Manna MC and Singh GB 2000. Impact of land use and management practices on organic carbon dynamics in soils of India. In: Lal R, Kimble JM, Stewart BA (Eds.), *Global Climate Change and Tropical Ecosystems, Advances in Soil Science*. CRC Press, Boca Raton, FL, pp. 261-281.

Thakur NS, Attar SK, Gupta NK and Gupta B 2015. Fodder availability from traditional agri-silvi-horticulture systems: Requirement and deficit w.r.t. livestock status in mid hills of Western Himalayas-A case study. *Journal of Tree Sciences* **34**(2): 22-27.

Thakur NS, Gupta NK and Gupta B 2011. Biomass, carbon stocks and CO_2 removal by shrubs under different agroforestry systems in Western Himalaya. *Indian Journal of Ecology* **38**(1): 14-17.

Thakur P, Thakur CL and Bhardwaj DR 2024. Dynamics of soil physical and chemical properties under fruit tree based agroforestry systems in sub-humid agro-climatic zone. *Indian Journal of Ecology* **51**(6): 1156-1159.

Woomer PL 1999. Impact of cultivation of carbon fluxes in woody savannas of Southern Africa. *Water Air and Soil Pollution* **70**(1-4): 403-412.

Wu J, Huang J, Han X, Gao X, He F, Jiang M, Jiang Z, Primac RB and Shen Z 2004. The Three Gorges Dam: An ecological perspective. *Frontiers in Ecology and the Environment* **5**: 241-248.

Received 16 August, 2025; Accepted 10 November, 2025